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Evaluation of Modelling of Flow in Fractures

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***Abstract*—Heat-transport is important for geothermal exploration. The presence of fractures can have a pronounced effect on groundwater and heat transfer.The inclusion of fractures into geothermal reservoir models on different scales is often still a difficult task. A comparison of approaches for flow in fractures has been carried out. A very simple approach is to simulate fractures with thin but highly conductive layers, for instance by applying the Cubic-Law. A more sophisticated approach, typically in FEM codes, is the application of lower dimensional (1D/2D) high permeable discrete elements with specific flow properties, following e.g. Hagen-Poiseuille or Manning-Strickler. However, such an approach typically fails while studying only partly saturated fractures. For studying the applicability of simplified fracture modellingapproaches a comparison with a CFD (Computational Fluid Dynamics) solution was performed. Furthermore a DEM (Discrete Element Method)approach has been illuminated. The various methodologies are studied by varying roughnesses,this way studying the versatility of the approach. The sensitivity of flow in fractures to various numerical parameters can be studied this way. A detailed analysis of temperature and flow using Péclet and Reynolds numbers helps to quantify the contributions of the different transfer processes.**

***Index Terms*—Fractures, Cubic Law, Discrete Elements, Computational Fluid Dynamics, Finite Element Method, Discrete Element Method**

I. Introduction

Geothermal energy is a cost effective, renewable way to process transfer energy and an important technology with respect to a change towards renewable energy. The increasing power demand, especially in developing countries,together with the limited availability of fossil fuels has led to increased effort in this field. The basic idea geothermal energy is to exploit the heat generated in the depth of the earth's crust, mainly by natural radioactive decay. The heat can be extracted by the circulation water in greater depths.Outside of volcanic regions a depth of more than 3 kilometers is necessary. It involves the drilling of boreholes, followed by the pumping of water to depths where the temperature of the rock is markedly higher than on the surface. The resulting vapor and water is collected by another borehole and passed through a steam turbine to produce electrical energy.The presence of fractures has a strong impact on the subsurface temperature distribution [1].

A more recent analysis compares the advances of geothermal modelling providing a holistic view on the current state of research involved [2]. Modelling of geothermal reservoirs is possible with a number of different codes. In this study, the use of the software FEFLOW 6.1, which is software devised by DHI WASY,has been proposed which will be used to analyse the situations of heat transfer and groundwater

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flow. FEFLOW allows the modelling of heat transport in the subsurface and the inclusion of fractures using discrete feature elements. The software and its capabilities have been illustrated multiple times by Ref. [3] and [4]. The modelling to simulate the actual network of fractures would be ideally done using the cubic law which will link the velocity to the fracture aperture and pressure. Other methods were employed due to the lack of computational power.

The modelling of flow through fractures bears an important role in the geothermal industry. With the advent of computational power the reservoir simulations in the geothermal industry are very useful in both in terms of industrial production as well as scientific study. The FEM codes like FEFLOW help in the simulation of heat transport and flow in a given geothermal reservoir. However in these simulations it is important to simulate the flow through fractures systems as fractures reservoirs encapsulate an imperative part of production and their geological study has been explain in detail by [5]. There is a marked difference in the methodology of production and extraction from a fractured reservoir which has been dealt by Ref. [6]. Hence from a scientific perspective it remains important to look into the modelling of flow in reservoirs as the flow in a reservoir rock cardinally controls the production. A stochastic numerical model was built and the flowtransport in fractured rock was penned out by Bear Ref. [7]. There have been numerous methods developed over the years to model the flow of fluid and heat transport in fractured rock by Ref. [8]. However in FEM codes like FEFLOW, the introduction of fractures is through discrete elements in the model of the reservoir. The modelling of the flow in these discrete elements can take various paths as the flow law can be varies according to the nature of the fracture involved. The finite element code has been elucidated and its applications for fluid flow in rock mases described by Ref. [9]. The issues and examples of geothermal processes has been described by Ref. [10]. However this maybe computationally intensive and the use of discrete elements is not possible in the case if unsaturated flow simulations. Hence an alternative is to look at the applications of CFD which may be used to model the flow in fractures. This can be used to model the flow in the fractures, serving to be both computationally efficient as well as accurate.

Analyzing results can be a complicated task, which has to be maneuvered in the direction of the field of applicability. Hence in this paper we will look at the temperature plots and the hydraulic head plots of the simulations to predict the outcome. Another interesting observation can be drawn using the Péclet number as shown by Ref. [11]. Since the validation of the flow in fractures cannot be carried out without the inclusion of field data, an approach through computational fluid dynamics has been sought. Computational Fluid Dynamics (CFD) is the art of simulating a flow of fluid in a given geometry. It is often used to assess the performance of engineering devices, to explore in a cost-effective manner several competing designs, or to provide understanding of flow processes within or around a given configuration.

The OpenFOAM® (Open Field Operation and Manipulation) Ref. [16] is a CFD Toolbox is afree, open sourceCFD software package produced byOpenCFD Ltd. It has an extensive range of features to solve anything from complex fluid flows and can be efficiently used in this case to model the flow in fractures. The application of CFD to the modelling of flow in fluids has been illuminated in the recent past [12].The modelling of fractures in rock masses has been taken on extensively using Discrete Element Method. It is possible to model their yield strength, the shear strength of fractures as well as the cross sectional area of fractures in rock using this method. Hence this paper aims to look at the prospects of the software 3DEC – an advanced code for the numerical modelling geotechnical analysis in discrete element blocks – to model the flow of fluids in fractures for elucidation of modelling flow with the aforementioned simulations in OpenFOAM and FEFLOW.

II. Model Setup

A. Conceptual Model

As a first step in model design FEFLOW requires the initial mesh extent where we define the range of the model in terms of distance in which the model exists. The model locale or dimensions have been defined in a coordinate system of 1 m times 1 m.The following simulations were composed of standard equation for saturated flow, and shock capturing was used in the upwinding.

B. Numerical Model

The groundwater flow equation is the basis upon which the flow phenomenon is simulated. It is common practice to develop numerical solutions of the equation based on the specific boundary conditions. In the present case, a finite element grid was defined. The grid provides for the discretization of the data – which is

performed in both the horizontal and vertical directions as shown in figure 1. In the present case, the horizontal discretization was specified by defining a triangular mesh generator [13].

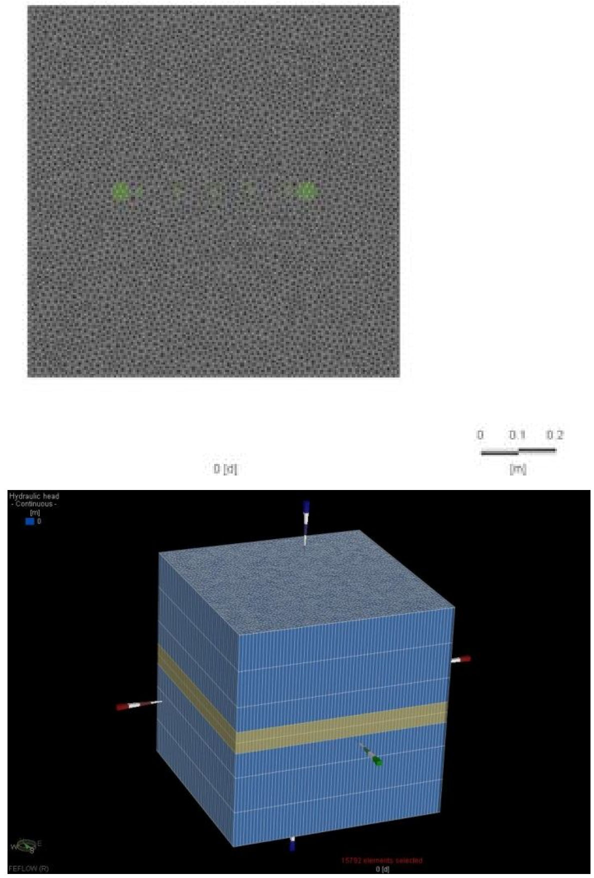

Figure1. Mesh of the Model (Top) three-dimensional model view (Bottom)

It is necessary to define a set of boundary conditions (BC) for the simulation of the model. By default, all model boundaries in FEFLOW are impervious. FEFLOW supports four basic types of boundary conditions for flow, mass and heat transport. For the current model we adopt the Dirichlet type BC which requires us to define a boundary head condition as well as a boundary condition for the temperature. The temperature BC is defined at the injection well as well giving it a temperature of one degree Celsius which acts as a tracer. Using groundwater a tracer has been discussed in detail before Ref. [14]. The boundary condition for the well as also defined where the pumping rate of the injection and extraction well maybe assigned.The software FEFLOW allows the user to define initial conditions for the model in question. Hence the initial conditions such as the temperature, hydraulic head, conductivity, porosity, etc.

III. SIMULATIONS

The simulation is carried out by FEFLOW according to the defined time period after the entire initial and boundary conditions are fulfilled. The corresponding charts of temperature, head, pressure, etc. are plotted automatically by FEFLOW.The study has been divided into distinct cases based on the flow in fractures using discrete features and a highly conductive layer.

The models are mainly of four types and their flow has been studied below. The well has been given a boundary condition with a temperature which acts as a tracer. The models have a pumping and extraction well which have been placed 0.5 m apart. The wells are being pumped at a rate of -5 m^3 (injection) and 5 m^3(extraction) per day. Fractures in the form of highly conductive slices /discrete features were added in the model in the middle slice. The model adopted the Dirichlet type BC which requires us to define a

boundaryhead condition as well as a boundary condition for the temperature. The boundary conditions for head and temperature was uniformly set to zero across the model. The figures below represent the flow results for the models described above. Figure 2 is the model where a highly conductive layer of hydraulic conductivity of 100 m/s has been used in the slice for the simulation of fracture flow. Figure 3 represents fracture flow using discrete features and apply Manning Strickler law to the flow in the fractures, where the aperture used is 0.005 m. Figure 4 represents fracture flow using discrete features and apply Hagen-Poiseuille flow to the fractures, where the aperture used is 0.005 m. Figure 5 represents fracture flow using discrete features and applies Darcy law, where the aperture used is 0.005 m. The flow equations used in the simulations are:

Darcy flow law:

$$\vec{q} = -\frac{k}{\mu}(\nabla p) \tag{1}$$

k is the hydraulic conductivity, μ is the viscosity

Hagen-Poiseuille flow law(Cubic form) :

$$\vec{q} = -\frac{b^2}{12\mu}\left(\frac{dp}{dx}\right) \tag{2}$$

b is the aperture, μ is the viscosity.

Manning-Strickler flow law :

$$v = -\frac{\tau r^{\alpha/2}}{\sqrt[4]{\|\nabla h\|^2}} I(\nabla h) \tag{3}$$

h is hydraulic head, α is a constant, r is the aperture, I is the flow gradient and τ is the friction factor.

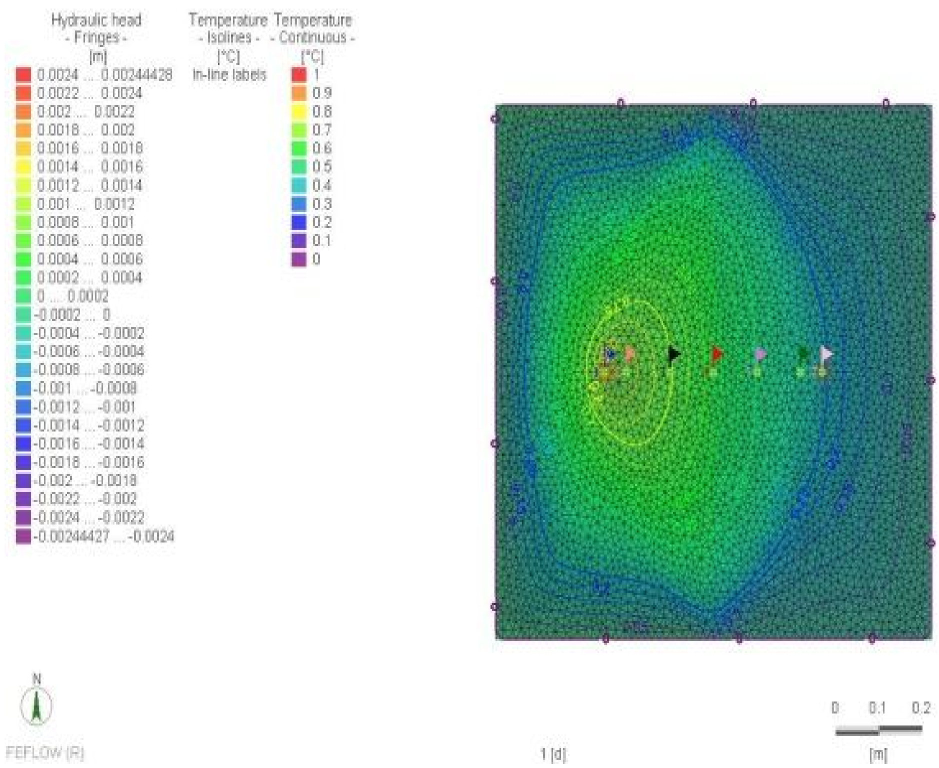

Figure 2. Hydraulic head and temperature results for model with highly conductive layer as fracture

The Péclet number was calculated using an IFM Plugin to the software. The plugin was coded using Microsoft Visual Studio and programmed in C++. Pécletnumber was calculated according to the formula:

$$Pe = \frac{L\vec{v}}{a} \tag{5}$$

$$a = \frac{\lambda}{\rho c} \tag{6}$$

The characteristic length was computed by calculating the value of the volume of the element divided by the area of the top face of the element. This provides an equivalent of the characteristic length in the equation mentioned above.

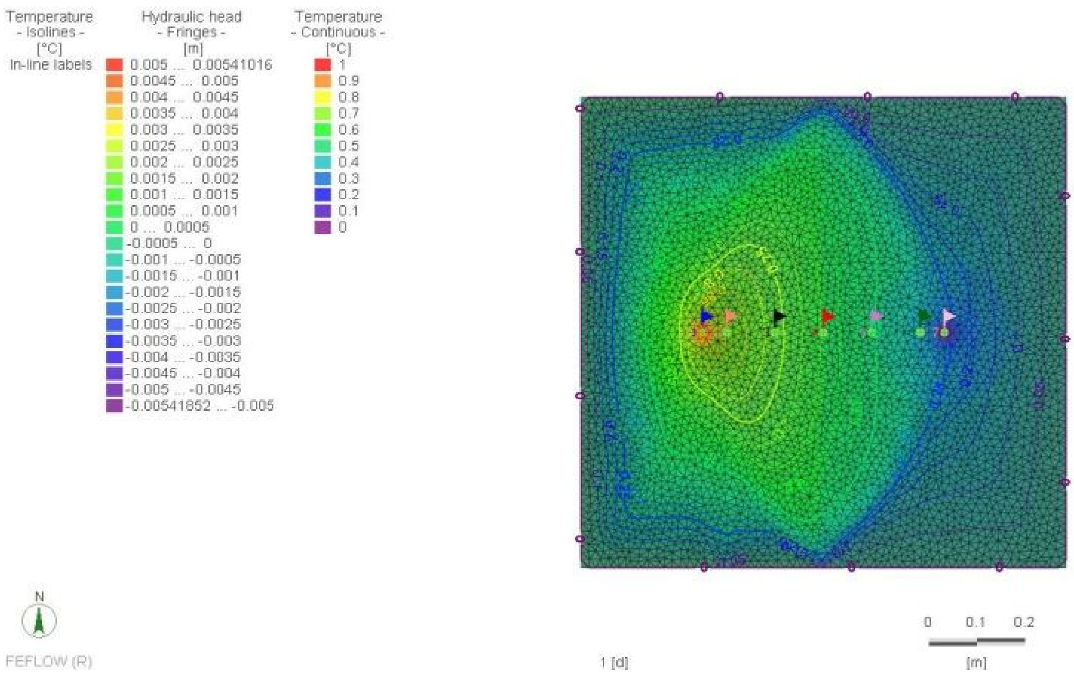

Figure 3. Hydraulic head and temperature results for model with discrete features using Manning-Strickler flow

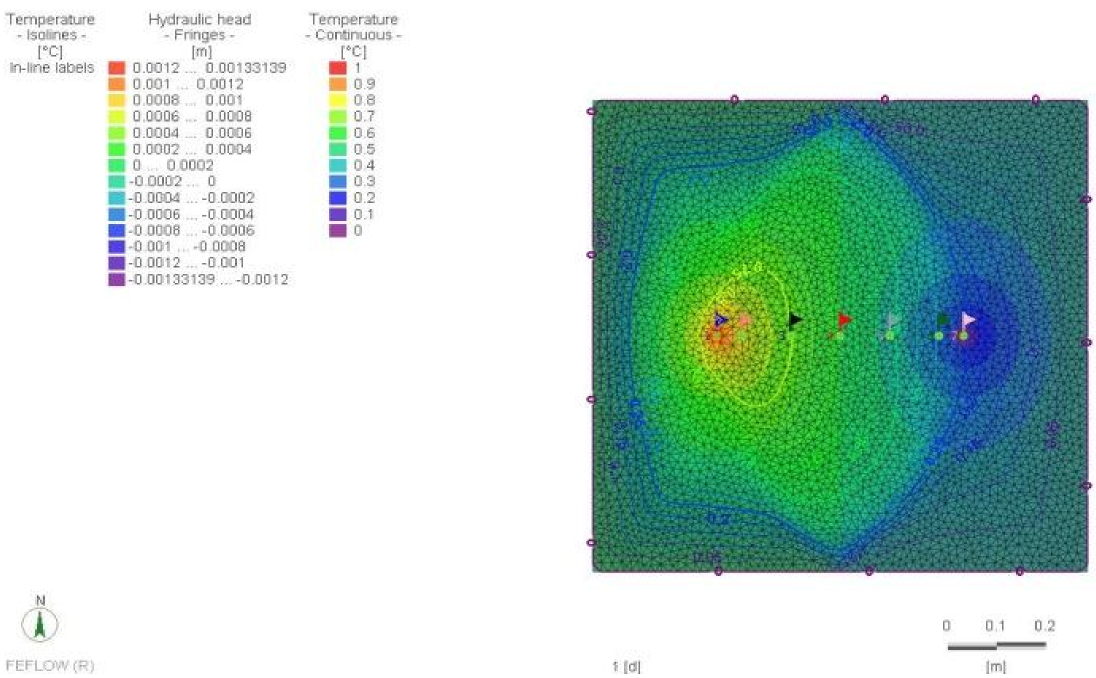

Figure 4. Hydraulic head and temperature results for model with discrete features using Manning-Strickler flow

IV. OPENFOAM MODELLING

Groundwater flow simulations based on Darcy's law are typically limited to laminar flow. However in cases where geothermal reservoirs are employed the flow can become turbulent in cases of involvement of hot dry rock, fractures and geothermal wells where water is pumped at a high velocity. Hence it becomes vital to

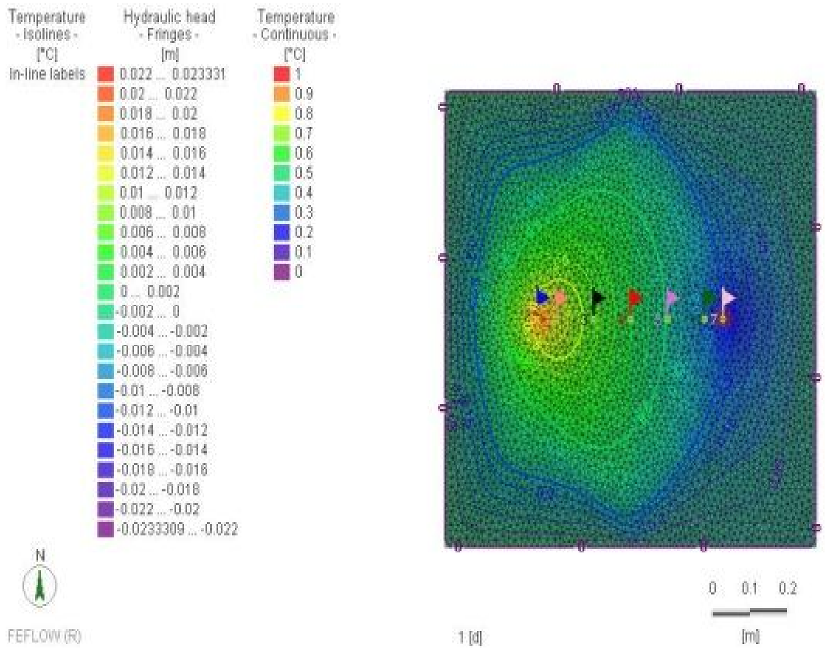

Figure 5. Hydraulic head and temperature results for model with discrete features using Darcy flow

examine the flow both in the cases of laminar as well as turbulent flow in OpenFoam. Thus in the following models have been created to study the flow using laminar as well as turbulent models. The models have been meshed and computed in OpenFoam. The post processing has been performed using ParaFoamtogether with ParaView.

Since OpenFoam is a 3D solver the meshing has been done for a 3D geometry however the analysis itself is in 2D as two of the faces have been declared empty. The geometry of the model consists of a rectangle with a length to diameter ratio of 15. The length of the model is much larger as compared to the diameter so as to make sure that the flow is fully developed in the denoted simulation time. The mesh grading can be specified in OpenFoam. The mesh grading was simple and uniform throughout the model. Refinement of the mesh was not necessary near the walls as OpenFoam provides the wall function which is an alternative to the refinement of the mesh. The meshing of the model as well as a screen of the model has been displayed below in figure 6.

```
----------------
Mesh Information
----------------
  boundingBox: (0 0 0) (1.5 0.1 0.01)
  nPoints: 49282
  nCells: 24000
  nFaces: 96640
  nInternalFaces: 47360
----------------
Patches
----------------
  patch 0 (start: 47360 size: 40) name: inlet
  patch 1 (start: 47400 size: 40) name: outlet
  patch 2 (start: 47440 size: 600) name: upperWall
  patch 3 (start: 48040 size: 600) name: lowerWall
  patch 4 (start: 48640 size: 48000) name: frontAndBack
```

Figure 6.   Meshing information

OpenFoam requires the selection of solvers at the early preprocessing stage. The solver used in all these simulations is called pisoFoam. PisoFoam has been defined in the OpenFoam libraries as standard solver which is used for incompressible flow. It can be used to simulate both laminar as well as turbulent flow. The turbulent flow has been simulated using the RAS (Reynolds-Averaged Simulation) package..

The models have been built on the pisoFoam which consists of an inlet, outlet, top wall and bottom wall. The inlet velocity has been defined, and the inlet pressure in variable. The outlet pressure of the models is zero. This thereby permits the user to measure the pressure difference at points of interest which when divided by the velocity will give us the required result.

The model has been run for a period of 10 seconds. Figure 7 shows the plot of the pressure at the end time of the simulation. Figure 8 gives the plot of the velocity at the end time of the simulation. These simulations can be used for comparison with the FEFLOW simulations of fracture flow. The software uses the K-epsilon model for the simulation with the general turbulence momentum and energy equations which have been described in detail by Ref. [15].

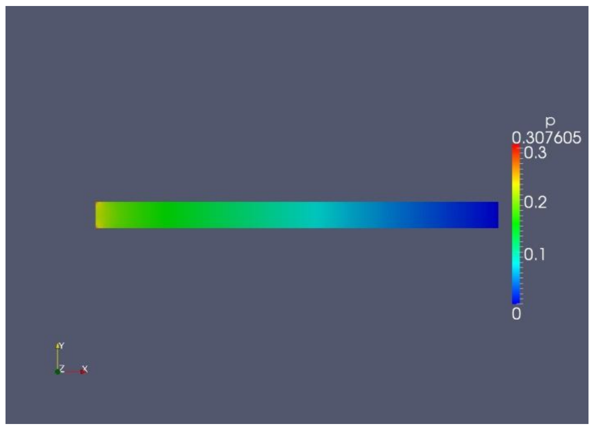

Figure 7. Pressure at end time with Surface Roughness (5) & Turbulent Flow

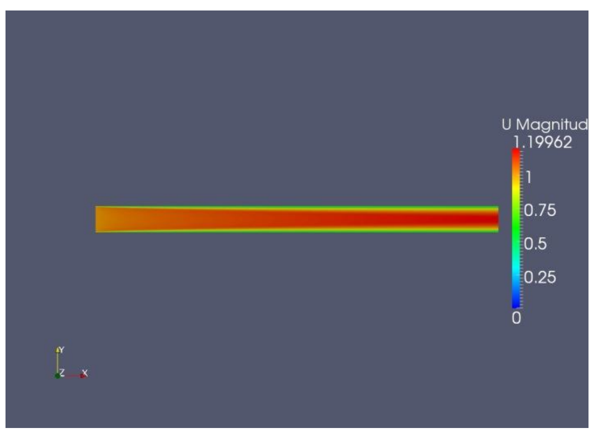

Figure 8. Velocity at end time with Surface Roughness (5) & Turbulent Flow

V. FEFLOW COMPARISON WITH OPENFOAM

A simple FEFLOW model was built in which flow was simulated without the use of wells or temperature conditions. The model was simulated with a flow which is driven by a pressure gradient equivalent to the result from the CFD simulation in OpenFoam. The simple groundwater equation has been employed without mass or heat coupling. The pressure gradient was fixed to 0.31 kPa and the flow was simulated in four regimes namely flow in a highly conductive layer which behaves close to flow in fracture, discrete features used to describe fractures using Hagen-Poiseuille, Manning-Strickler and Darcy flow laws. The ratio of the velocity and the pressure gradient has been compared to the OpenFoam results. Table 1 and Figure 9 display

the nodal Darcy velocities for the models generated in OpenFoam. In the case of the model where a highly conductive layer has been used to depict the fractures, it can be seen that there is a uniform flow in the middle and center of the model however at the edges there seem to be an increase in the Darcy velocity. This is because the boundary conditions have been applied to the borders of the model which results in certain edge effects. However this does not influence out study as we are interested in the velocity in the center of the model which is not affected by developing flow or boundary conditions.

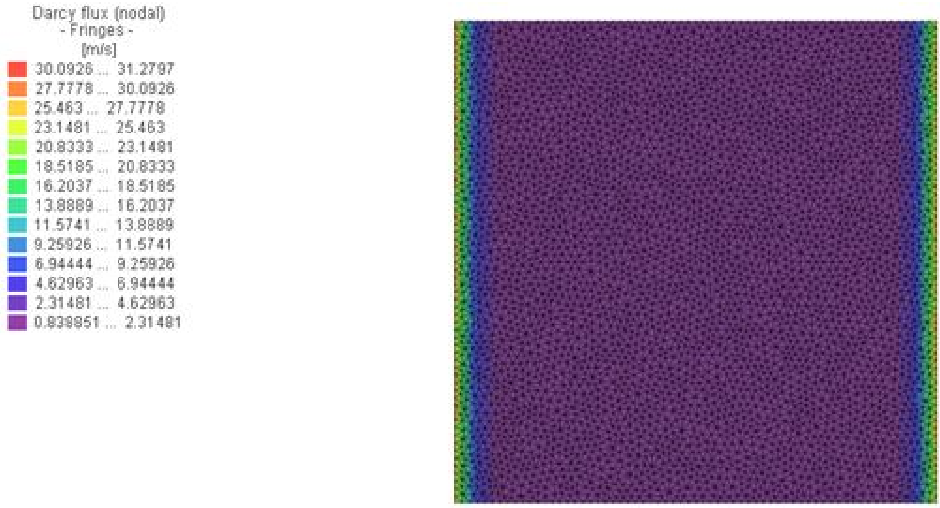

Figure 9. Darcy velocity of fracture flow in FEFLOW using simple pressure gradient of 0.307 KPa for comparison with OpenFOAM. Image of the model with slices with high hydraulic conductivity used to represent fractures

TABLE I. VELOCITY AND PRESSURE OF THE FRACTURE FLOWS SIMULATED IN FEFLOW AND OPENFOAM

Type of Flow	Velocity	Pressure Gradient	Velocity/Pressure Gradient	Hydraulic Conductivity (K)	Roughness Coefficient	Aperture	Hydraulic Aperture
Hagen Poiseuelle	1.12	0.307	3.64		NA	0.1	0.0075
Manning Strickler	1.16	0.307	3.77	NA	50	0.1	NA
Darcy	1.15	0.307	3.74	37.5	NA	0.1	NA
High Conductive Layer	1.15	0.307	3.75	30	NA	0.1	NA
Laminar without surface roughness	0.15	0.414	0.36	NA	NA	0.1	NA
Laminar with surface roughness	0.22	0.417	0.53	NA	NA	0.1	NA
Turbulent without surface roughness	1.09	0.179	6.09	NA	NA	0.1	NA
Turbulent with roughness aperture 5mm	1.19	0.307	3.88	NA	NA	0.1	NA
Turbulent with roughness aperture 10mm	1.31	0.734	1.78	NA	NA	0.1	NA

VI. 3DEC MODELLING

Rock fractures and flow of fluid media in them have been studied extensively, but the role of the fractures in this matter remains unobserved in most cases. The use of 3DEC in modelling the flow of a fluid under a pressure gradient has been studied such that a comparison can be made between the flow of the fluid in case of using a discrete element approach as opposed to a CFD approach can be lucrative. The flow of fluids in fractures modeled in 3DEC assumes a modified cubic law for flow.This approach can be easily incorporated into OpenFoam, nevertheless in case of 3DEC, there is a sharp distinction made between the properties of the

rock and the fracture. The deformability of the fracture is larger than that compared to the rock; the shear resistance of the fracture due to the roughness can be efficiently incorporated into the model.

A model can be constructed so that the simulation of flow of fluid in fractures incorporates the deformability of the fractures as well as the shear resistance due to the roughness property. Although the simulations in this paper assign a roughness coefficient to the flow of fluid, this is partly conjectured; actual conditions will have to be calibrated using lab and field studies. The incorporation of an accurate simulation of flow will have to incorporate rock properties and most importantly the fracture properties though a yielding constitutive model. A joint constitutive model can be setup using 3DEC which can be used to represent a more realistic scenario of flow of fluids in fractures and joints.

VII. Conclusions

Simulation of fractures using simple methods is possible and such as using a highly conductive layer to act as a fracture in a flow simulation is not only possible but efficient. However the properties of the slice or layer like the hydraulic conductivity, aperture etc. has to be pre-determined such that they may have as a fracture network. From the fracture simulations in FEFLOW using a geothermal injecting well, we see that the maximum hydraulic head is produced in the case of Darcy flow law used in discrete features. Following this is Manning-Strickler, Hagen-Poiseuille and the layer with high conductivity in order of reducing head. The analysis of the Péclet number in the figures on the left shows us that the convective heat transport is limited to the wells and the area surrounding the wells only. The Péclet numbers are high in the case of Darcy and Manning-Strickler flow. The comparison of Darcy flow and Manning Strickler flow in discrete features shows us that the Darcy flow is more efficient in terms of computational efficiency and Péclet number.

The best method to adopt this would be the simulation of fracture networks using a CFD method using a simple case and then using this result to preset the properties of the slice or layer in question.

We have to take cognizance of the fact that the simulation using discrete features to represent a fracture is possible as well in FEM codes like FEFLOW. However these processes tend to demand a bit more computational power, but nonetheless efficient. The flow itself of the fluid in the fracture is also very important and the discrete features help us choose the flow equations which increase the control of the user in these simulations. There is a large scope for research in terms of CFD simulation of flow in fractures. The determination of the roughness coefficient and the surfaceroughness aperture can be actively studied and modeled using FEM as well as CFD to make the simulation of flow in fractures more efficient.

An alternative presents itself in the case of DEM, the simulation of fractures is efficient with many opportunities for modification. The incorporation of such flow into ground water modelling software or reservoir simulation software will be beneficial, and this represents scope for future study due to the nature of versatility in the application of flow in fractures in 3DEC. Moreover, the flow law used in these fractures parallels that used in FEFLOW in some cases. This leads to reason where it would be beneficial to model the flow of fractures using DEM.

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